

Figure 6. Depth-resolved values of specific conductivity and dissolved arsenic for surface water within the northern, central and southern portion of the HBHA Pond. The general location and sampling date is listed with each figure set. The horizontal scales for specific conductivity and arsenic are identical for each panel within each figure set. The scales for the North figure set span a larger range than shown for the Central and South figure sets. The vertical scale is identical for all figure sets. All water samples were collected from a pontoon boat except for North-09/01, which was collected from the North Multi-level sampling station.

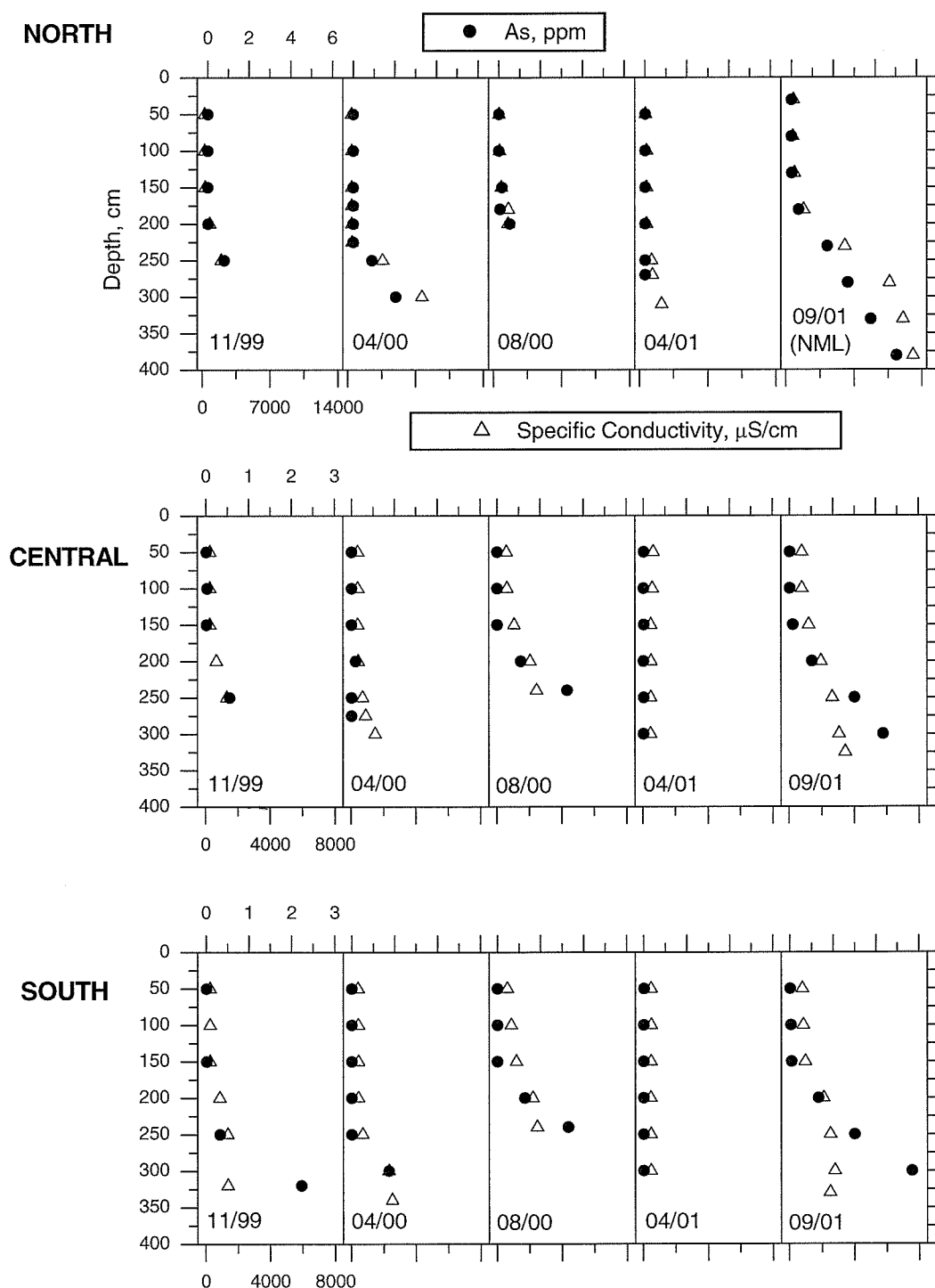


Figure 7. Trends in specific conductivity and dissolved arsenic observed at NML sampling station from April 5, 2001 to September 14, 2001. The location of NML within the pond is illustrated in the aerial photograph to the right (MassGIS, 1995). The location of each screened level for the NML sampling station is referenced to tubing well location TW07 to the right of the data figure. Screened intervals NML-1 through NML-8 are located within the HBHA Pond water column. Screened interval NML-9 is located within the HBHA Pond sediment layer and screened interval NML-10 is located within the underlying sandy aquifer. For consistency in presentation, the depth of each screened interval for all sampling dates has been referenced to the water level on April 5, 2001.

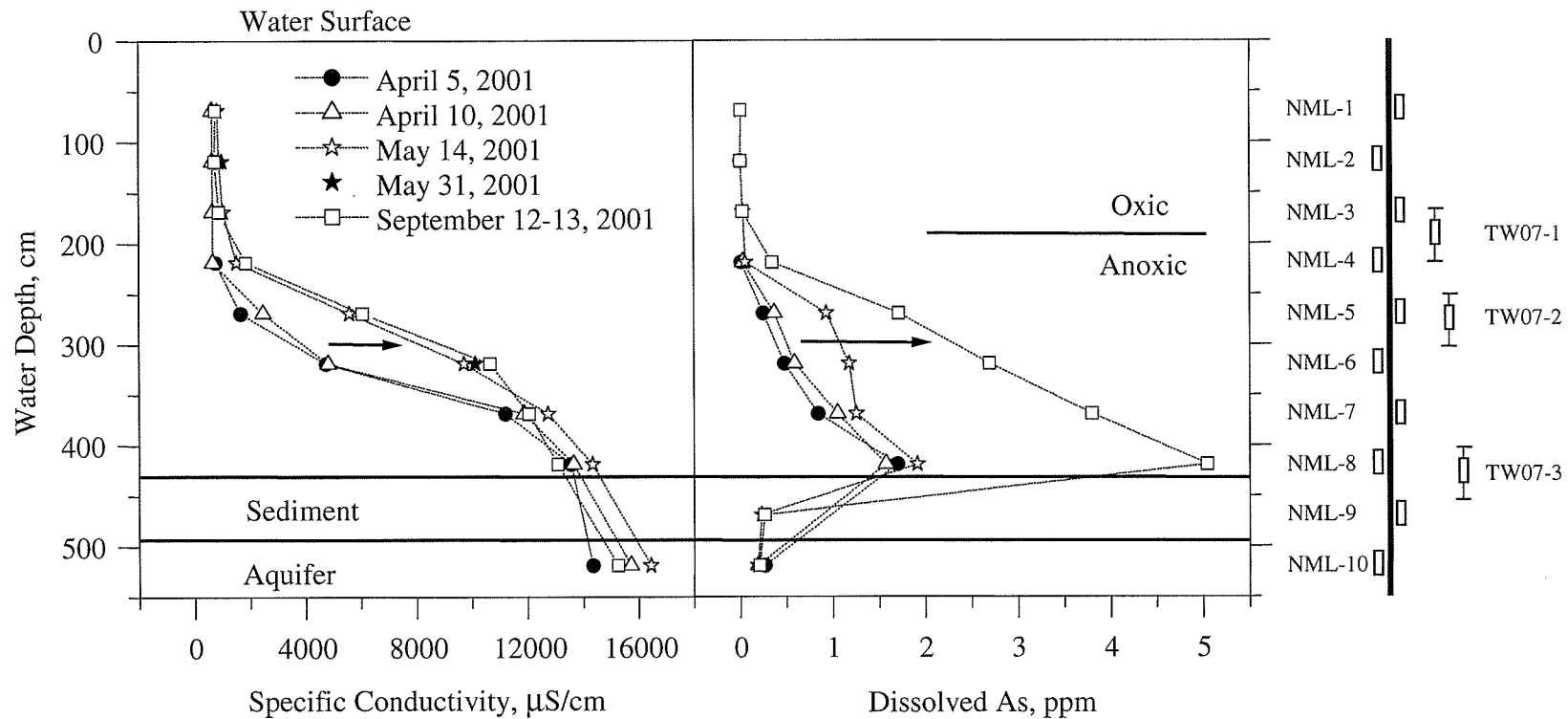
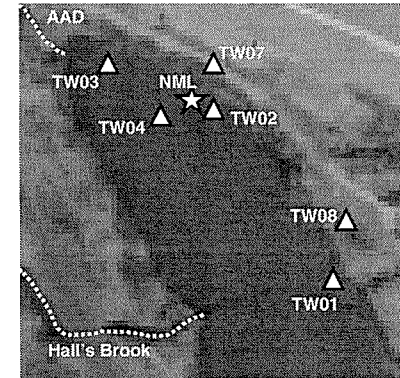


Table 1. Trends in dissolved arsenic during sampling dates April 4, 2000 and April 2, 2001 at the HBHA Pond north sampling location and the period April 5, 2001 to September 14, 2001 for tubing well location TW07 and screened intervals for the NML sampling station with approximately similar depth. NM = not measured, ND = not detected

Sampling Location	Dissolved As, ppb		Sampling Location	Dissolved As, ppb			
	April 4 2000	April 2 2001		April 5 2001	April 10 2001	May 14 2001	Sept. 13-14 2001
WN 150	ND	11	NML-3	NM	ND	33	30
<i>TW07-1</i>	<i>1705</i>	<i>879</i>	<i>TW07-1</i>	<i>880</i>	<i>NM</i>	<i>NM</i>	<i>812</i>
WN200	ND	15	NML-4	ND	33	60	349
WN250	904	15	NML-5	251	372	933	1718
<i>TW07-2</i>	<i>746</i>	<i>1066</i>	<i>TW07-2</i>	<i>1114</i>	<i>NM</i>	<i>NM</i>	<i>1334</i>
WN300	2040	257 ¹	NML-6	480	591	1179	2695
--	--	--	NML-7	844	1054	1253	3800
<i>TW07-3</i>	<i>81</i>	<i>130</i>	<i>TW07-3</i>	<i>174</i>	<i>NM</i>	<i>NM</i>	<i>209</i>
--	--	--	NML-8	1702	1576	1917	5043
--	--	--	NML-9	NM	NM	231	261

¹ WN300 depth was 310 cm on April 2, 2001.

3.4 HBHA Wetland and Wells G&H Wetland Sediments

Sediment grab samples were collected within the HBHA Wetland and the Wells G&H Wetland to assess the distribution and stability of sediment-associated arsenic down gradient of the HBHA Pond. Sediments were frozen immediately after collection and processed under an inert atmosphere within a glove box to prevent oxidation. Sediment pore water was collected from thawed sediments and characterized to assess geochemistry and arsenic concentration (see Table F.5). Sediment pore waters contained elevated concentrations of As ranging from approximately 160 to 670 ppb, which did not correlate directly with the sediment arsenic concentration for all sediments. Following removal of the major portion of pore water, the sediments were dried at room temperature within the glove box and then analyzed for total element concentrations (see Table F.6).

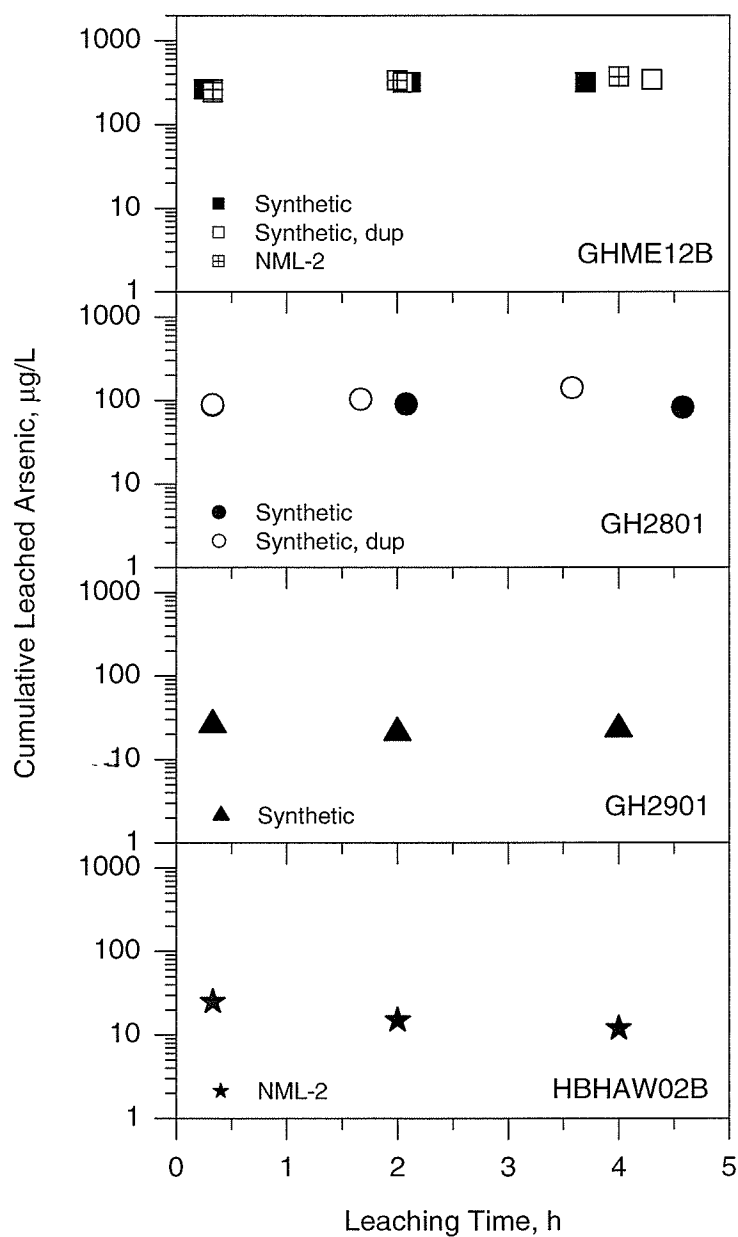
Arsenic release in the oxic leaching tests for the sediments are shown in Figure 8 and documented in Table F.7 (Appendix F). Measurements of the oxidation-reduction potential show that sediment suspensions become more oxidizing over time. In all cases, most of the leached arsenic had been released within a 30-minute reaction period (Figure 8, Table F.7). Sediment samples GHME12B and GH2801 showed the greatest As release with 341 ± 27 ppb (24 ± 1 $\mu\text{g/g}$ sediment) and 112 ± 42 ppb (3 ± 1 $\mu\text{g/g}$ sediment) over a 4-hr period, respectively. Arsenic release was less for sediments GH2901 and HBHAW02B with concentrations of 23 ppb (0.2 $\mu\text{g/g}$ sediment) and 12 ppb (0.1 $\mu\text{g/g}$ sediment), respectively.

The extent of rapid arsenic release for all sediments indicates there is a relatively labile fraction of arsenic within the dried sediments. Since all sediment splits had residual pore water prior to drying, a portion of the rapidly released As could be attributed to re-dissolution of this As pool. The equivalent concentration of As derived from this source was estimated for all leach

experiments based on measured pore water concentrations and the mass of residual pore water in each split (see Table F.7). For sediments GHME12B and GH2801, residual pore water accounted for less than 4% and 26% of the leached As, respectively. In contrast, the estimated As concentration derived from residual sediment pore water could account for all of the leached arsenic for sediments GH2901 and HBHAW02B.

The concentration of leached As was consistently lower than the measured pore water concentration for all sediments samples. The in-place chemistry for these sediments was reducing based on the observation of high concentrations of ferrous iron. The oxidation of ferrous iron, leading to precipitation of iron oxides, is a likely process for the reduction in dissolved arsenic during sediment oxidation. However, as shown for sediments GHME12B and GH 2801, there is limited capacity for this process to prevent arsenic release and transport. Both sediment pore water measurements and oxic leach tests indicate that wetland sediments may be a long-term source of As to ground water and surface water. Consistent with observations in the HBHA Pond, the greatest risk of As release from sediments occurs under reducing conditions.

Figure 8. Arsenic released from wetland sediments (see Tables F.5 and F.6) as a function of time for oxic leach tests (see Table F.7). Explanation of legend descriptors: 'Synthetic' = synthetic shallow pond water, 'Synthetic, dup' = duplicate experiment with synthetic shallow pond water, 'NML-2' = water sample collected from NML-2 sampling location in HBHA Pond.



4.0 Conceptual Site Model

4.1 Arsenic and BTEX in Ground Water

The ground-water monitoring data collected during the period of this investigation indicate that arsenic and BTEX compounds derived from the ground-water aquifer underlying the Industri-Plex Superfund Site are discharged into the HBHA Pond. Current and historical data indicate that ground-water arsenic is derived from a much larger region than BTEX. The primary source of BTEX compounds originates from the eastern portion of the ground-water aquifer underlying the Industri-Plex Superfund Site. A general schematic for the distribution of these contaminants within the ground-water aquifer is shown in Figure 9. The concentration of dissolved arsenic observed at fixed monitoring points (tubing wells) indicate that there is an insignificant level of attenuation occurring within the ground-water aquifer upgradient to the HBHA Pond and Wetland. The site characterization effort for BTEX compounds under this investigation was insufficient for the purpose of delineating natural processes degrading these contaminants within the ground-water aquifer. The primary focus of the effort was to assess if these compounds were being discharged into the HBHA Pond and could thus serve as a source of degradable carbon. In this respect, the continued discharge of BTEX compounds into the HBHA Pond in part drives the microbial processes that govern the redox chemistry of this system.

4.2 Arsenic in HBHA Pond

The HBHA Pond was constructed in the early 1970s as a hydraulic equalization basin for flood control. The HBHA Pond is approximately 200 feet wide by 1100 feet long (in direction of water flow) and has a depth of approximately 20 feet in its deepest portion (see Figure A.7). The sides of the HBHA Pond are generally steep and the depth of water at the outlet is typically one foot or less during baseflow. The geometry of this basin coupled with the distinct difference

in surface water and ground water density are the likely cause for continued stratification of the water column. The impact of stratification within the HBHA Pond on the fate of As derived from ground water is discussed below.

In general, the geochemical processes active within the ground-water aquifer underlying the Industri-Plex Superfund Site and down gradient wetland area are similar to those observed at acid mine drainage sites. However, the ground water underlying the site is well buffered preventing acidification within the aquifer and down gradient wetland. Oxidative dissolution of iron sulfides contained within waste materials deposited on site results in the continued production of dissolved iron and sulfate (Davis et al., 1994). The aquifer redox chemistry is sufficiently reducing to facilitate transport and discharge of iron as Fe^{2+} into the HBHA Pond. In oxic zones within the HBHA Pond, the oxidation of Fe^{2+} results in the precipitation of iron oxides that scavenge dissolved arsenic concurrently discharged from the ground-water aquifer. Dissolved organic compounds (anthropogenic and natural) discharged into the HBHA Pond provide a readily degradable source of food for the microbial community within the sediments (Suarez and Rifai, 1999; Hertkorn et al., 2002/ and references therein). This microbial activity within the deeper portions of the HBHA Pond results in the generation of an anoxic zone in which iron and sulfate reduction processes are active. This redox stratification appears to be maintained for most of the year due to the stability of the chemocline within the water column. The formation and maintenance of this chemocline is driven by the discharge of primarily low conductivity water at shallow depths (Hall's Brook) and high conductivity water at deeper depths (site-derived ground water). The chemical stratification that is typical for the HBHA Pond is depicted in Figure 10.

The overall processes controlling arsenic chemical cycling within the HBHA Pond water column and sediments are depicted in Figure 11. As discussed previously, ground-water monitoring data indicate that there is a continual source of arsenic into the HBHA Pond. Water column measurements throughout the HBHA Pond indicate that the highest concentration of dissolved arsenic is confined to the deeper depths within the pond. The dissolved arsenic concentration near the sediment-water interface is generally higher than the predominant concentration of dissolved arsenic in ground-water discharge. The mass of dissolved arsenic in the HBHA Pond water column is controlled by a balance between the observed sources and removal processes listed below:

- | | |
|----------------|---|
| Source | 1) ground-water discharge
2) suspended solid or sediment dissolution and re-suspension |
| Removal | 1) sorption to solids deposited in the sediment
2) sorption to suspended solids produced by iron oxidation-precipitation
3) discharge at the HBHA Pond outlet |

The concentrations of solid phase arsenic observed in the sediments and the dissolved arsenic observed near the sediment-water interface indicate that there is incomplete removal onto sediments. Sediment solids rich in iron, sulfur and organic matter sequester a fraction of the total arsenic at the sediment-water interface. It is unclear which of these phases controls arsenic partitioning during deposition. The remaining fraction of total arsenic at the sediment-water interface can be attributed to ground-water discharge and dissolution of iron oxides. Dissolved arsenic derived from these two inputs diffuses upward within the water column and is sequestered from solution during oxidation and precipitation of ferrous iron at the oxic-anoxic interface. The production and dissolution of iron oxides behaves as a steady-state process as long as the chemical stratification is maintained within the water column. Thus, while dissolved

arsenic concentrations can become high at depth, shallow water in the oxic zone remains much lower in dissolved arsenic.

A vertical profile of select chemical parameters is shown in Figure 12. These vertical profiles show a snap shot in time of the outcome of the competition between suspended solids or sediment dissolution and ferrous iron oxidation-precipitation at the oxic-anoxic interface within the water column. Dissolved Fe and As concentrations decline to near-zero values at a depth above the oxic-anoxic interface. A turbidity maximum is also observed at this interface, which can be attributed, in part, to the observed maximum in particulate iron. The particulate iron is dominated by iron oxides, which serve as a sink for arsenic. As the iron oxides settle back to the sediment-water interface, they begin to dissolve via reductive mechanisms causing the reduction in turbidity and particulate iron, and, subsequently, the release of arsenic.

Generalized chemical reactions controlling arsenic distribution between the sediments and the water column are depicted in Figure 13. Oxygen at shallow depth is derived from discharge from Hall's Brook and gas exchange at the air-water interface. The Atlantic Avenue Drainway may also serve as an intermittent source of oxygen. Electrons involved in iron- and sulfate-reducing processes are derived from microbial degradation of organic matter within the water column and sediments. Natural and contaminant dissolved organic compounds within the HBHA Pond water column provide a substrate for microbial metabolism, which controls the redox chemistry of the system. Wick et al. (2000) have observed that benzene degradation rates are greatest in the aerobic zone within the HBHA Pond, but degradation of fuel components can still be an active process in anaerobic zones (Suarez and Rifai, 1999). While ferrous sulfides are a likely source for arsenic uptake at the bottom of the HBHA Pond water column, insufficient

data is available to rule out sorption to other solids that are formed or deposited at the sediment-water interface.

Figure 9. Generalized schematic of arsenic and BTEX plumes in the ground-water aquifer upgradient from the HBHA Pond and Wetland. Image was derived from May 1995 aerial photograph obtained from MassGIS.

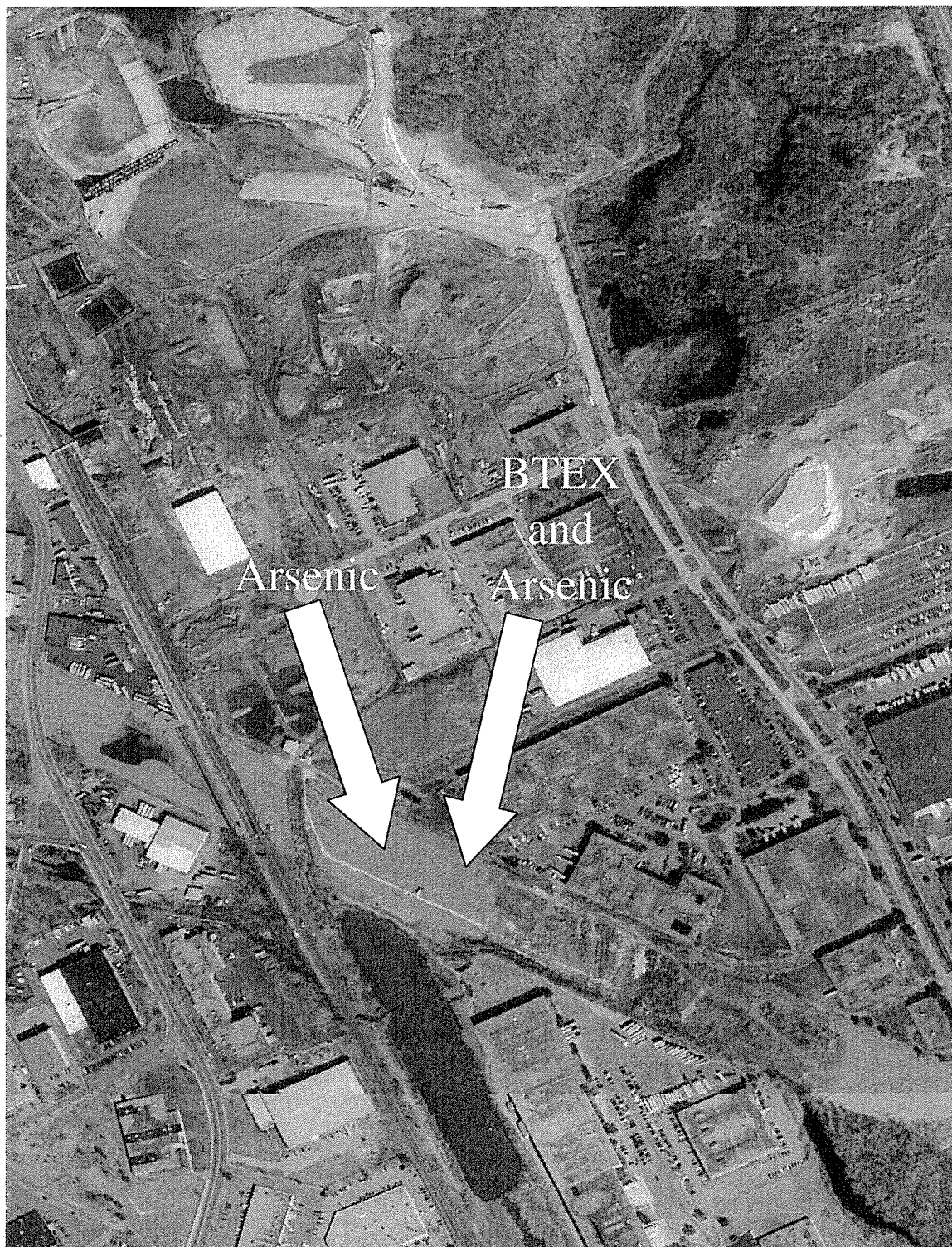


Figure 10. Conceptual diagram depicting important processes controlling water column chemistry in the HBHA Pond. Predominant inputs of water into the HBHA Pond include site-derived ground water and Hall's Brook. The inset graph depicts the chemical stratification that is common throughout the year. Iron and sulfate reduction processes are active at the sediment-water interface and within the shallow sediments.

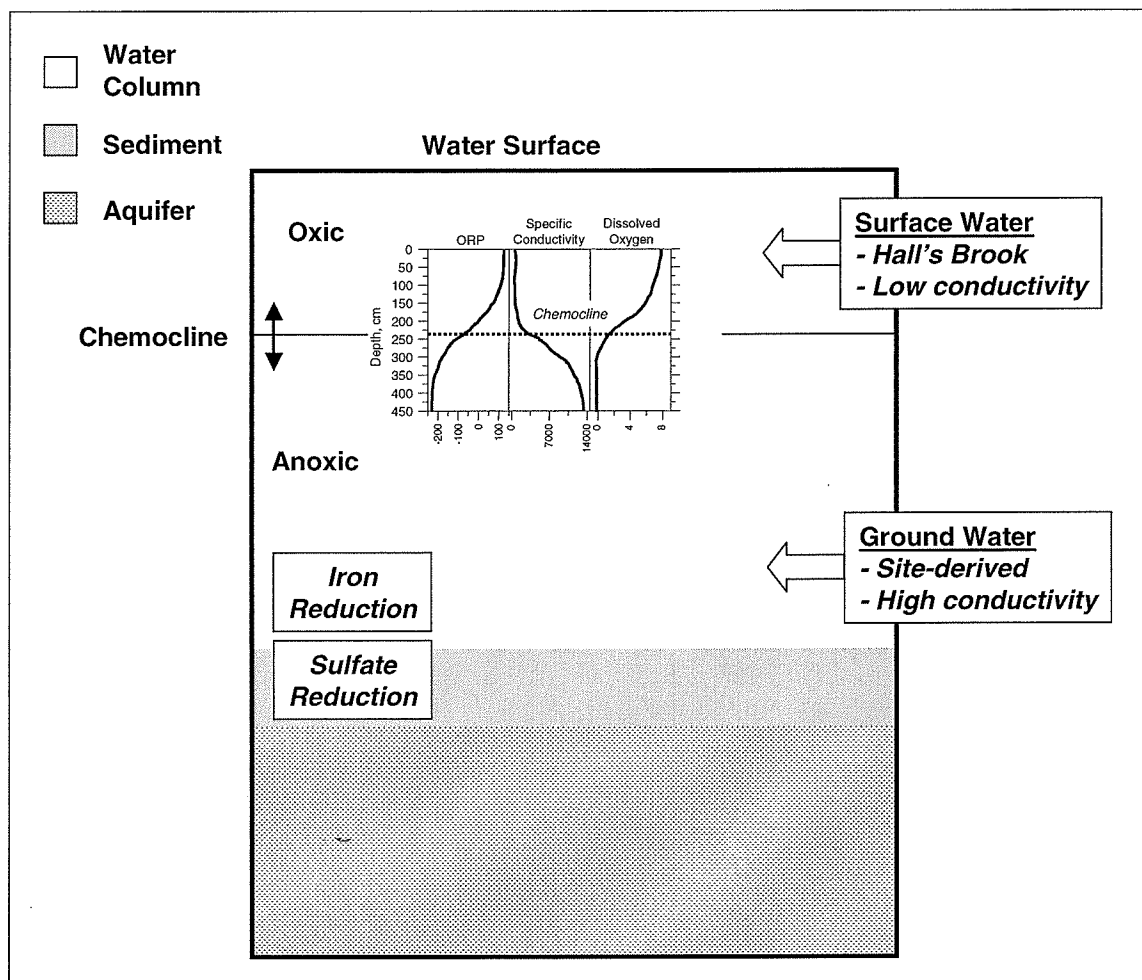


Figure 11. Diagram of the general processes controlling arsenic distribution between surface water and sediments within the HBHA Pond. Surface water inputs of arsenic include discharge of site-derived ground water and dissolution/re-suspension of contaminated sediments. Removal of arsenic from surface water occurs during iron oxidation-precipitation and settling at the chemocline and partitioning of arsenic to reduced sediments during diagenesis.

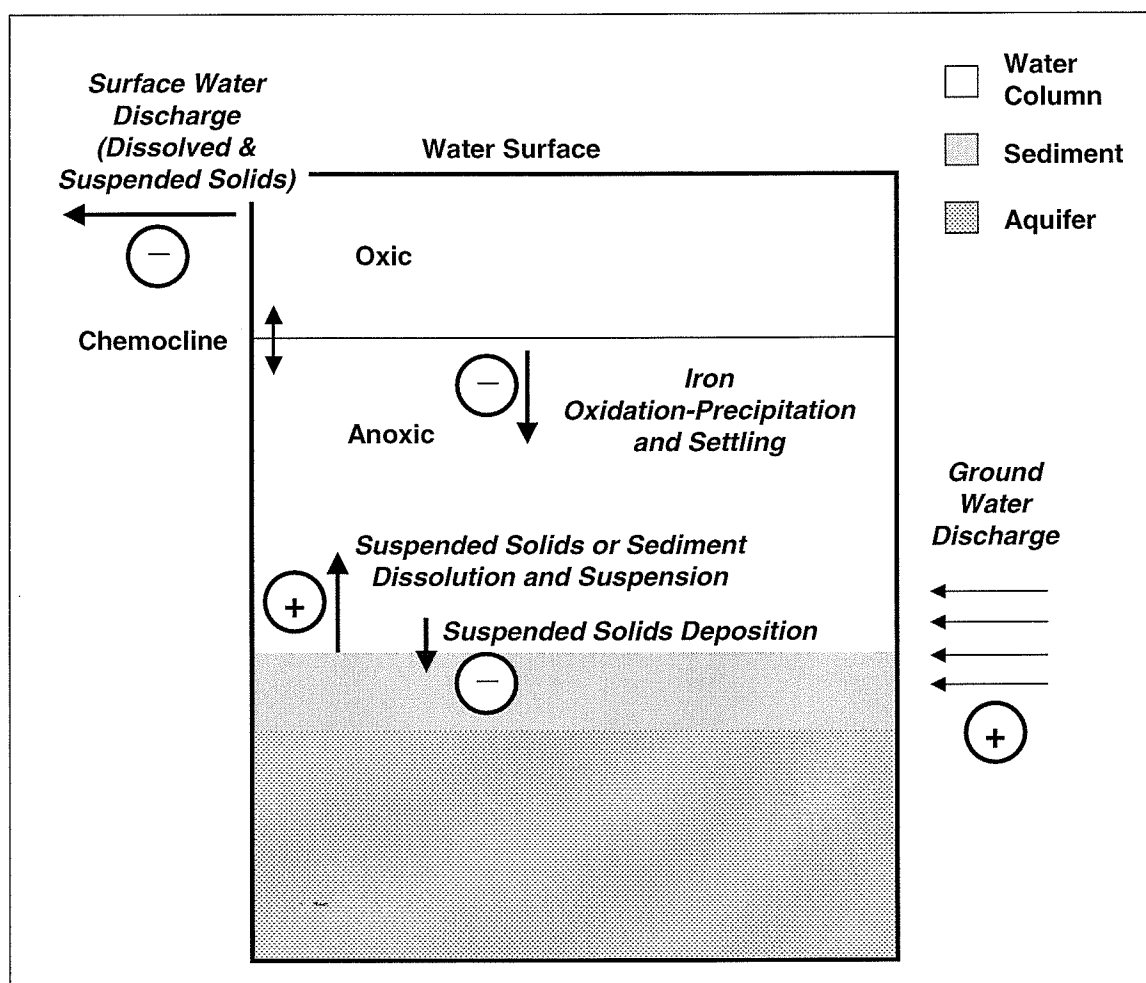


Figure 12. Depth trend for HBHA Pond geochemistry and dissolved/particulate As/Fe for South sampling location during December 1999. Particulate As/Fe was calculated by difference between total As/Fe in unfiltered and filtered samples. The concentration maximum for particulate Fe and As coincide with the turbidity maximum within the water column at this location.

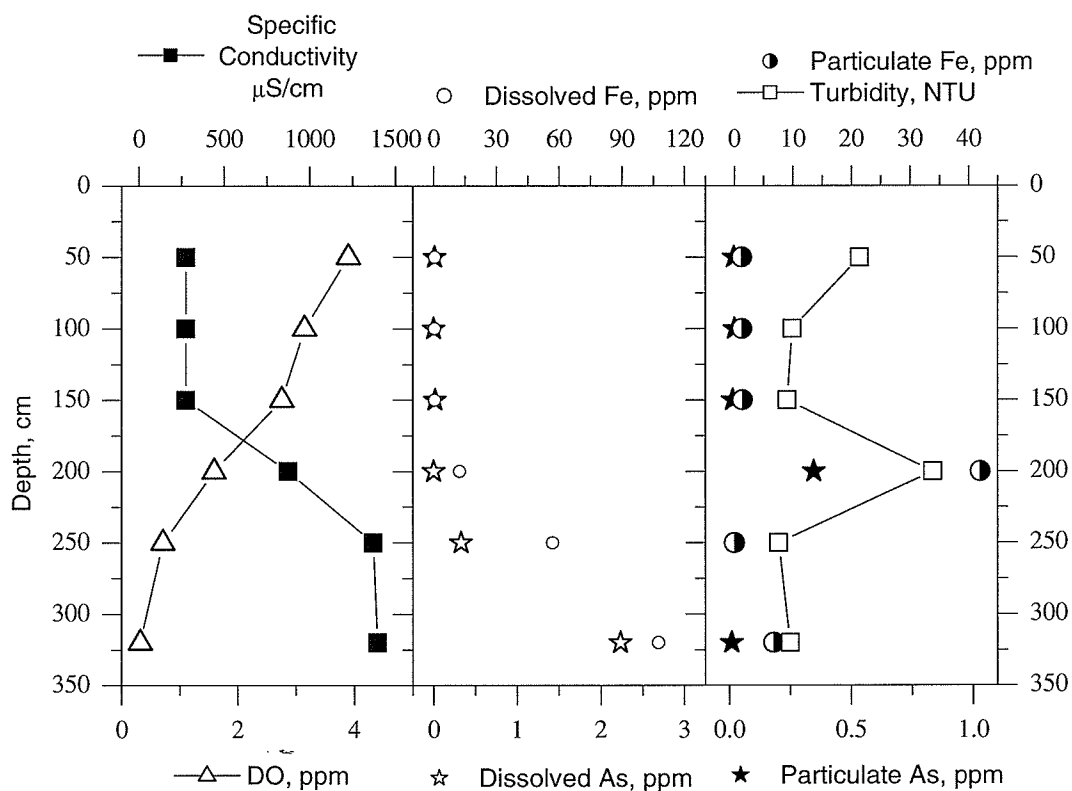
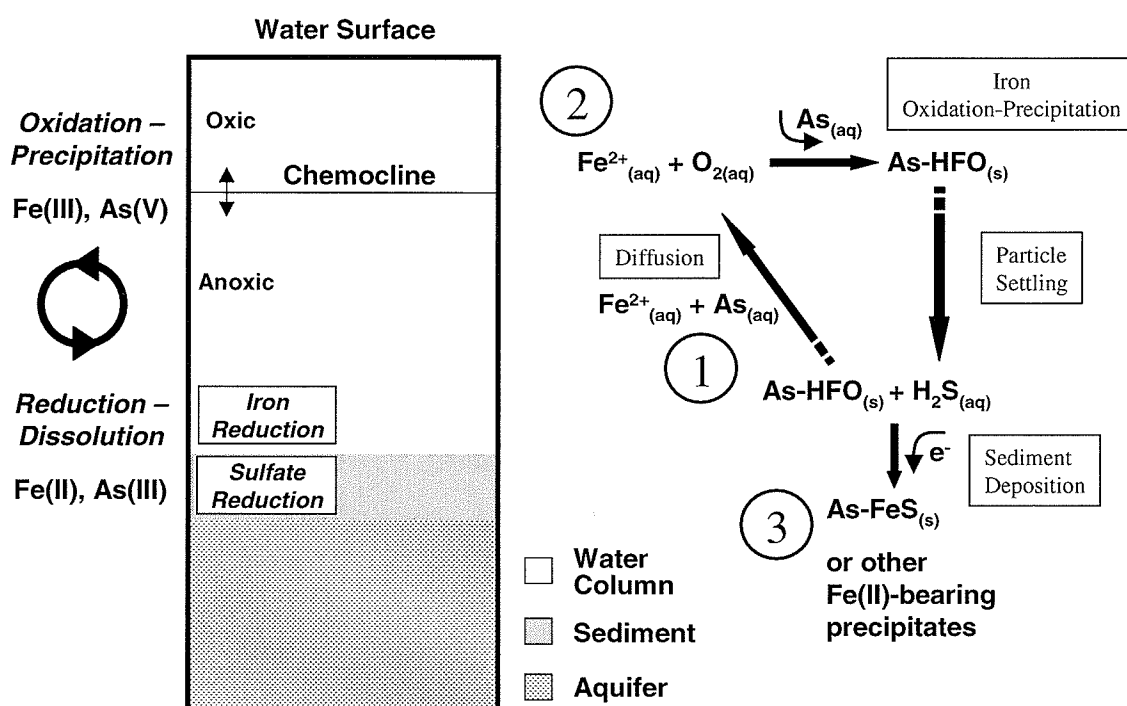


Figure 13. A general schematic of the chemical reactions controlling the internal iron and arsenic distribution between the aqueous phase and solid phase within the HBHA Pond. 1) Arsenic bound to authigenic ferric oxides is desorbed during reductive dissolution. 2) Dissolved arsenic is sorbed to ferric oxides precipitating at the chemocline due to ferrous iron oxidation. 3) Arsenic is repartitioned to ferrous sulfides or other Fe(II)-bearing precipitates during reductive dissolution of authigenic ferric oxides that settle out from the chemocline.



5.0 Assessment of Remedial Alternatives

5.1 Natural Attenuation Processes within HBHA Pond

Assessment of ground-water data collected during the ORD NAS and historic data collected within the Industri-Plex Superfund Site and GSIP Study Area indicate that the primary discharge point for contaminated ground water is into the HBHA Pond. Long-term monitoring at the HBHA Pond surface water discharge indicates that dissolved arsenic is typically below a concentration of 100 ppb. This indicates that arsenic discharged via site-derived ground water is partially sequestered within the HBHA Pond. However, observed release of arsenic from shallow sediments confirms the instability of iron oxides deposited on the bottom of the HBHA Pond. Although the HBHA Pond retains a significant fraction of As derived from ground-water discharge, it still supplies a continual flux of As to down gradient wetlands and the Aberjona River.

The critical factors maintaining arsenic at depth within the HBHA Pond hypolimnion are 1) the presence of a fairly stable chemocline and 2) the high capacity for arsenic sorption to iron oxides (Ford, 2002) formed at the oxic-anoxic transition zone. The capacity for arsenic sequestration from the HBHA Pond water column is dependent on a continual supply of ferrous iron into the system. The arsenic sequestration capacity will decline concurrent with a decline in ferrous iron from the upgradient aquifer. Since performance of the HBHA Pond for arsenic removal is also dependent on continued stratification of the water column, assessment of the long-term sedimentation capacity is also an important factor. The bathymetric profile of the HBHA Pond shown in Figure A.7 (Appendix A) indicates that the western portion of the pond (1-2 meters or 3-7 feet) is shallower than the eastern portion (>3 meters or >9 feet). Presumably this bathymetric profile is in part due to sediment deposition from Hall's Brook and the AAD.

Projections of sediment erosion or turnover within the HBHA Pond will depend on knowledge of modifications of the pond geometry over time.

Since the source term for arsenic (and iron) within the upgradient aquifer is poorly defined, it is difficult to assess the long-term capacity of the HBHA Pond. Given this level of uncertainty, it is recommended that a long-term monitoring strategy be implemented that continuously tracks arsenic and redox chemistry within the aquifer and the HBHA Pond. A proposed strategy is outlined below. Recommendations for site monitoring and potential remediation apply only to discharge of contaminated ground water into the HBHA Pond and are not intended to address potential contaminant migration in surface water and ground water down gradient from the HBHA Pond.

5.2 Engineered In-situ Technologies

Mitigation of arsenic discharge from the Industri-Plex Superfund Site to the down gradient wetland would benefit from control of arsenic release from suspected on-site source terms. However, the feasibility of this approach is limited by the widespread distribution of contaminated soils and hide piles throughout the site. Ground-water monitoring data from this study and historic site assessment activities indicate that there has been little diminution in the concentration of arsenic in site-derived ground water. The extent to which the HBHA Pond could continue to serve as a partial sink for arsenic would be extended by elimination of ground-water inputs of arsenic. This could be achieved via emplacement of a permeable barrier that would intercept and remove arsenic from the ground-water contaminant plume prior to discharge into the HBHA Pond. The use of zero valent iron (ZVI) as a reactive media for arsenic removal has been evaluated at the bench scale (Lackovic et al., 2000; Su and Puls, 2001). These studies show that ZVI has a significant capacity for arsenic removal, but there are no long-term studies

to evaluate the longevity of this removal capacity and the stability of sequestered arsenic. Long-term monitoring at sites where ZVI has been used to treat TCE and chromium ground-water contamination indicate that high specific conductivity water reduces the performance capabilities of this material (Wilkin et al., 2002). However, it should also be noted that the chemistry controlling arsenic sequestration in the HBHA Pond is in part poised by the characteristics of the discharging ground water. Changes in ground-water composition, such as a reduction in dissolved iron concentration, are expected to negatively impact the performance of the HBHA Pond for arsenic removal. Given these limitations, there is no immediate advantage to installation of a permeable reactive barrier over a long-term monitoring strategy for the HBHA Pond. In addition, treatment of up gradient ground water will only remove one of the sources of As to the down gradient wetlands and the Aberjona River. Release of sediment-bound As will still act as a second source for contaminant migration.

5.3 Long-Term Site Monitoring

As stated in Section 5.1, the HBHA Pond currently serves to remove a fraction of the ground-water arsenic derived from the Industri-Plex Superfund Site. However, the ability of the HBHA Pond to function in this capacity over the long term will be controlled by 1) continued maintenance of the chemical stratification within the water column and 2) continued supply of iron and sulfate from site ground water for the production of iron oxides and sulfides.

As shown via HBHA Pond water column sampling during April 2001, high surface water flow events can perturb the chemical stratification. While the chemocline was re-established within the HBHA Pond, there is insufficient monitoring data to track the impact of these transient flow events on the long-term performance of the HBHA Pond for arsenic sequestration. Forecasting the impact of surface flow events is critical due to site development, which can

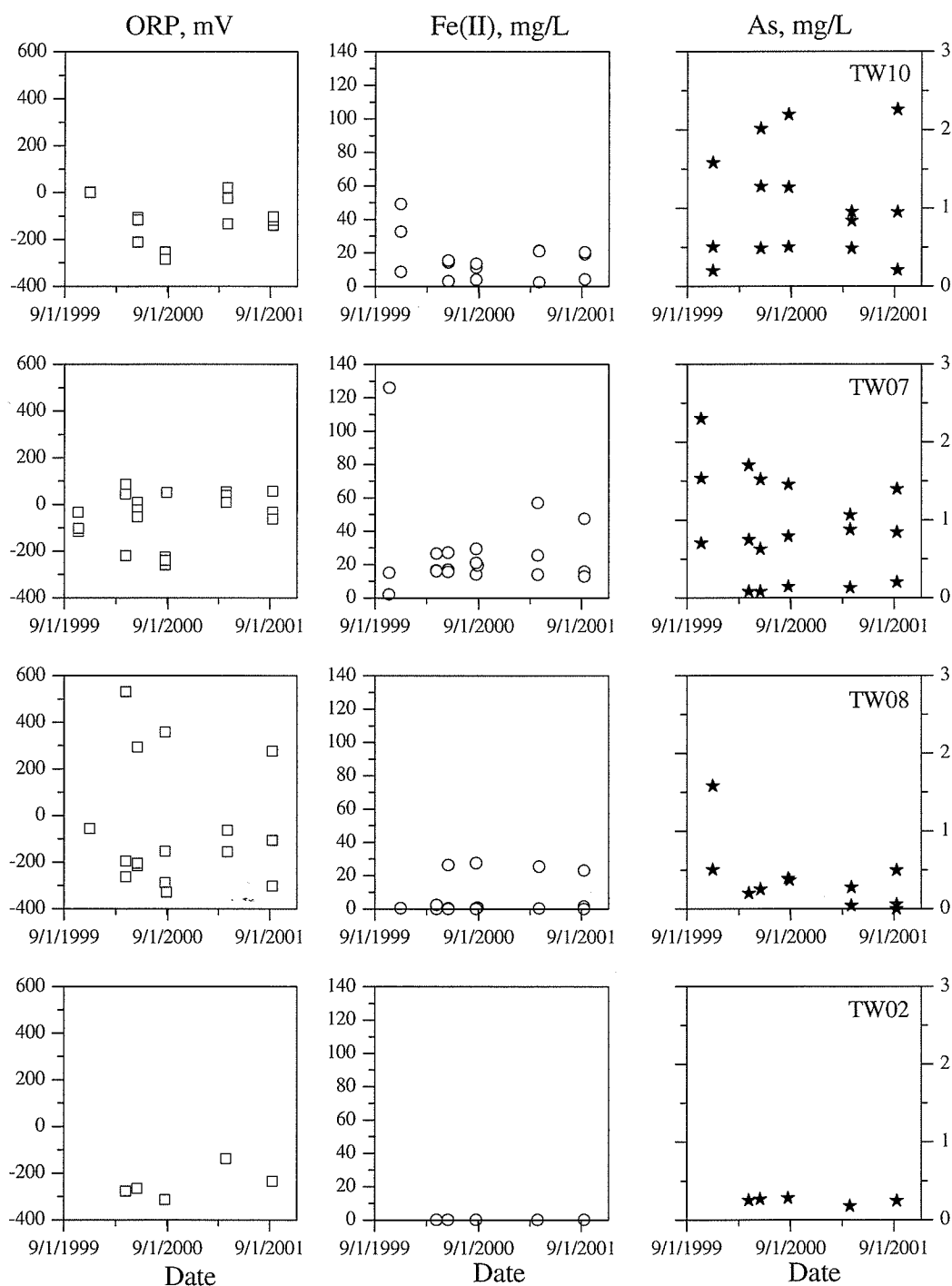
modify patterns in surface runoff into the HBHA Pond via the Atlantic Avenue Drainway. It is recommended that a long-term monitoring program incorporate input and output flow measurements for the HBHA Pond in order to establish whether the major flow event occurring at the end of March 2001 was anomalous or is likely to occur on a more frequent basis. Note that continued discharge from Hall's Brook should be maintained, since this continuous source of fresh water helps maintain chemical stratification within the HBHA Pond. As demonstrated by depth-resolved measurements, the highest concentration of dissolved As occurs at the bottom of the HBHA Pond and is relatively invariant throughout the year. This mass of dissolved As will be distributed throughout the water column during turnover, leading to increased mass flux of As at the shallow outlet. This is a critical factor, since the HBHA Pond is a potential long-term source of arsenic transport to the Aberjona River.

Site development may also exert an influence on the geochemistry of the shallow aquifer underlying the Industri-Plex Superfund Site. The paved area adjacent to the Regional Transportation Center (RTC) limits the amount of oxygen introduced into the shallow aquifer by gas exchange or recharge from precipitation. It is suspected that chemical conditions within this region of the saturated aquifer will become more reducing over time. It is uncertain what impact changes in aquifer redox chemistry will exert on the long-term release and mobility of arsenic. Examination of trends in ORP, dissolved ferrous iron and dissolved arsenic for a representative set of ground-water monitoring locations over time do not reveal a change in aquifer redox chemistry since the installation of the Regional Transportation Center (Figure 14). However, insufficient time may have passed to observe large-scale changes in aquifer chemistry, since this development was completed in late Fall 2000. The RTC overlies a region of the aquifer in which high arsenic concentrations were observed at the beginning of this study period (see discussion

of snap-shot ground water locations in Section 2.1). Since the RTC property occupies most of the area that can be developed on the western portion of the site (see Figure A.5, Appendix A), it is anticipated that post-installation monitoring data will be of value for projecting future arsenic flux into the HBHA Pond.

It is recommended that a more comprehensive site monitoring strategy be implemented in the near-term to better track performance of the HBHA Pond system and detect possible failure. The current focus for site monitoring has entailed extensive evaluation of surface water inputs and discharge points within the HBHA down to Mishawaum Road. In order to properly assess system performance, it is recommended that a permanent ground-water monitoring network be established within the aquifer upgradient and down gradient to the HBHA Pond. The network should be sufficient to document the extent of the arsenic contaminant plume and its elimination down gradient to the HBHA Pond. Contaminants of concern and the general redox chemistry of ground water should be monitored concurrent with surface water sampling events. In general, quarterly sampling will provide sufficient frequency to monitor the dynamics of the ground-water plume and the HBHA system, but it is recommended that additional efforts be made to assess system response to storm events. Consistent with requirements set forth in the EPA OSWER Directive on monitored natural attenuation, establishing a long-term monitoring plan for performance monitoring and evaluation is a critical component to application of this remedial technology (USEPA, 1999). Assessment of seasonal patterns in arsenic mobility and sequestration within the HBHA Pond is required to establish the long-term viability of natural attenuation as a partial remedy to mitigate arsenic discharge down gradient to the HBHA Wetland and Aberjona River.

Figure 14. Time trends in oxidation-reduction potential (ORP), dissolved ferrous iron, and dissolved arsenic at ground-water monitoring locations down gradient from the Regional Transportation Center located within the Industri-Plex Superfund Site boundary. Locations of ground-water monitoring points are shown in Figure A.5 (Appendix A). Data from all depths are shown together for locations TW10, TW07 and TW08.



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Appendix A

Summary of maps showing ground-water, surface water, and sediment sampling locations within the Industri-Plex Superfund Site and GSIP Study Area, and results of bathymetric survey in HBHA Pond.